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TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

DPST-74-366

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TO: J. M. BOSWELL

FROM: H. P. OLSON *H. P. Olson*
REACTOR ENGINEERING DIVISION

SPRAY COOLING OF DROPPED IRRADIATED ASSEMBLIES

INTRODUCTION

Charge and discharge operations were analyzed to identify improvements with regard to cooling of irradiated fuel in abnormal situations. Recommendations will be transmitted to Manufacturing Division (reference 1). These studies and recommendations will in part provide the basis for a budget item to improve safety of charge and discharge operations for FY 1977.

One emergency cooling situation that was analyzed involves irradiated

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Classified by: G F M
G. F. Merz, Supervisor
Reactor Engineering Division

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fuel that is dropped out of the discharge machine. It was concluded that this incident can be restricted to slug type assemblies such as the Mark 31A; no unpreventable mechanism was identified for dropping a multi-tube assembly with long integral fuel tubes, such as the Mark 16. This memorandum presents an analysis of cooling irradiated slug assemblies of current designs with the existing water spray system.

SUMMARY

Calculations indicate that pieces of current slug assemblies of any length can be cooled satisfactorily (i.e. minimal activity release) with an external spray. The most demanding slug assembly in current use is the Mark 31A with two concentric slug columns. With a spray rate sufficient to keep the outer surface wet, the temperature of the outer slugs would be $\leq 100^{\circ}C$. The temperature of the hottest inner slugs would probably be in the range of 460 to $630^{\circ}C$, depending on the degree of rib contact. Some cladding melting might occur if rib contact is extremely poor, but substantial release of fission products would not be expected at temperatures under $700^{\circ}C$. The minimum spray rate of the existing sprays ($0.2\ gpm/ft^2$) might have to be increased to keep the outer slug temperature under $100^{\circ}C$. Tests will be run to confirm the heat transfer calculations and to determine the required spray rate.

Future concentric slug assemblies, such as the Mark 15, probably would not be discharged with a higher decay heat than the Mark 31A because of the requirement for adequate heat removal if horizontal under water. The heat transfer tests and calculations for the Mark 31A are probably applicable to future slug assemblies.

DISCUSSION

Background

A fault-tree analysis of failures and malfunctions during charge and discharge operations (reference 1) identified the need for several modifications and additions to ensure cooling of irradiated fuel assemblies. These would include (a) adding a constraint to prevent lateral motion of the top of the assembly, and (b) staggering the inner and outer slugs for concentric slug assemblies; these modifications will keep the slug column intact and vertical should the top fitting or inner housing fail (the outer chuck prevents lateral motion of the mid-portion of the slug column, and the water pan supports the lower portion of the assembly after a drop of about ½-inch). In addition, a backup cooling system, independent of the present coolant supply to the load rod, will be recommended (reference 1) to ensure cooling capability. With these additions, the only failure identified that could cause slugs to drop out of the machine and require another method of cooling is failure of the inner housing with the water pan not under the assembly, e.g. failure while the assembly is being withdrawn from the reactor. The slugs could conceivably fall in an unpredictable manner and not re-enter the USH. The slugs could fall on the tank top or the reactor room floor, or lodge on the machine; the fragments might be long and assume a non-horizontal position.

No mechanism was identified for dropping an intact multi-tube assembly (eg, Mark 16) on the floor or tank top. Because of the high strength-to-weight ratio of the assembly of integral tubes, these assemblies would remain intact under almost any conceivable circumstance. The only mechanism identified that might possibly sever a multi-tube assembly is accidental x-drive of the discharge machine with the assembly partly in the USH; this can be prevented if it is indeed found to be possible.

Spray Cooling Calculations

With the cooling requirement for dropped components restricted to fragments of slug assemblies, adequate cooling by external sprays appears feasible. The current slug assemblies are more easily cooled by sprays than those previously considered (references 2, 3, 4, and 5) because there is no outer housing (no USH) as with the VB. Slugs can be cooled adequately by a spray impinging directly on the surface. Only the Mark 31A with two concentric slug columns presents a cooling problem, because heat from the inner slugs must be transferred to the outer slugs by conduction and radiation.

Calculated temperatures are shown below for a Mark 31A assembly cooled by an external spray sufficient to keep the outer surface wet with no evaporation (the average rate of the existing spray system, 0.6 gpm/ft^2 would be adequate).

	Maximum Temperature, °C		
Rib Contact	Hottest Outer Slug*	Hottest Inner Slug*	Average Inner Slug
2 ribs	77	460	363
1 rib	77	629	492
None	77	740	685

* Axial max/avg = 1.3

Details of the calculations are given in Appendix A. The temperatures are based on the following conservative assumptions.

1. Maximum decay heat, 29 kw per assembly, corresponding to the limit for adequate heat removal with an assembly horizontal under water. This corresponds to the decay heat about 14 hours after shutdown.

2. A rib contact heat transfer coefficient of 300 pcu/hr-ft^2-°C vs coefficients of 500 to 2000 in the literature (reference 6).

3. No credit for axial heat transfer. Results applicable to full length assembly.

4. No water penetration to inner slugs.

5. No credit for convection heat transfer across air gap, only conduction through stagnant air.

6. No credit for improved rib contact at high temperature due to thermal expansion or softening of the ribs. The clearance between ribs and fuel decreases as the inner slug temperature rises, and the nominal clearance of 0.030" is reduced to zero at 700°C. The maximum allowable clearance, however, is 0.050".

The most unfavorable position of the slug column fragment (eg, horizontal, vertical, or in between) is uncertain but probably not very important. The calculated temperatures assume the fragment axis is normal to the direction of spray water with regard to determining the amount of water falling on the fragment, eg, determining the projected area. The position that presents the smallest projected area is for one end of the fragment to point directly at a spray nozzle, in which case spray water would enter the fragment and directly contact the inner slugs. Regardless of the position of the fragment it is not likely that the outer surface temperature would be much higher than 100°C because vaporization of the spray water would provide fairly effective cooling. If the slug should be vertical the rib contact coefficient would be lower (but probably not less than 300 pcu/hr ft^2°C) but air convection due to the chimney effect and increased probability of water penetration would compensate.

Fission Product Release

The aluminum cladding could melt at a temperature as low as 577°C (build-in of silicon lowers the nominal 660°C melting temperature, as shown in reference 7), but significant fission product release would probably not occur at temperatures under 700°C. In tests at SRL, unirradiated Mark VII A slugs were heated in air to determine damage as a function of temperature (reference 8). At the threshold of cladding melting (650°C) uranium diffused into the cladding forming a brittle crust of UAl_3 (this phenomenon was also reported in reference 9, pg 62). At temperatures over 700°C the crust split open and the bare uranium oxidized. Oxidation was rapid at $\geq$ 800°C. The literature (reference 10, pg 30) states that massive lumps of uranium oxidize slowly in air at 500-700°C. The threshold temperature for substantial release of fission product gases is evidently about 700°C, and the calculations indicate that this temperature would be exceeded only on the hottest slugs if there is no rib contact at all.

Two other mechanisms for fission product release are a) diffusion, and b) ignition of uranium hydride (UH_3). Diffusion would be extremely slow at temperatures under 900°C, as shown in Appendix B. UH_3 ignites spontaneously in air, but no UH_3 would be present unless cladding penetration occurred while the slug was in the reactor (failed slug). Experience with UH_3 ignition on failed fuel elements (references 11 and 12) indicates the reaction was not violent and the bulk uranium was not consumed (the reaction stopped when the UH_3 was consumed). It is very unlikely that UH_3

4. SRL Monthly Report, DPST-62-1-1, pg 1-17 (Secret).

5. SRL Monthly Report, DPST-62-1-2, pg 1-8 (Secret).

6. N. D. Weills and E. A. Ryder, "Thermal Resistance Measurements of Joints Formed Between Stationary Metal Surfaces", Paper No. 48-SA-43, Transactions of ASME (1949), Vol. 71 pp 259-267.

7. "Hydraulics and Heat Transfer of Mark 22 Fuel Assemblies", DPSTM-22 (H), pgs IV-15 and IV-37, August 1972 (Secret).

8. W. H. Gleaves, "Behavior of Uncooled Irradiated Fuel of Natural Uranium", DPST-59-155, December 8, 1959 (Secret).

9. R. K. Hilliard, "Effect of Heating Irradiated Uranium, a Literature Survey", HW-52753, November 1, 1957 (Secret).

10. Chemistry of Uranium, Collected Papers, edited by J. J. Katz and E. Rabinowitch, Paper No. 2, pg 30, TID-5290, 1958.

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12. J. W. Croach, Letter to D. A. Miller, "Pyrophoric Materials in Slug Failures", DPST-55-519, (Secret).

13. F. H. Spedding, et al, "Uranium Hydride", Nucleonics 4, No. 1, pp 4-15 (1949).

14. J. J. Katz and E. Rabinowitch, "The Chemistry of Uranium", Part I, National Nuclear Energy Series, Division VIII, Volume 5.

15. DuPont Engineering Design Standards, DG Section, Volume II.

16. R. S. Barnes, et al, "Swelling and Inert Gas Diffusion in Irradiated Uranium", Proceeding of 2nd International Conference on the Peaceful Uses of Atomic Energy, p/81 UK, Vol. 5, pg 543.

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could be formed by spray cooling dropped slugs. Steam and uranium can react to form UH_3 at 250°C, but at higher temperatures (600-700°C) the reaction products are UO_2 and hydrogen (references 13 and 14). Uranium in a hydrogen atmosphere reacts to form UH_3, but the reaction rate decreases at temperatures above 225°C and approaches zero at 400°C as the decomposition rate equals the formation rate (reference 14). To form UH_3 during spray cooling of an assembly, water would have to penetrate to the inner slugs; but significant water penetration would cool the inner slugs and prevent cladding melting. Vaporization of only 3% of the spray water (at 0.6 gpm/ft^2) would remove all of the heat generated by the inner slugs. If water penetration should be delayed until after the cladding melted, then UH_3 could conceivably form if the slugs are cooled to < 400°C. In tests with unirradiated Mark VII A slugs (reference 8) heated to 700, 750, and 850°C and then cooled with a water spray, no evidence of UH_3 ignition was noted. Cladding failure and uranium oxidation occurred in the 750 and 850°C tests.

Spray Cooling Test

Tests are planned to provide a rough check on the calculated slug temperatures and to determine spray density requirements. The latter will probably be determined with a mockup of an outer slug column (eg, a pipe) with an internal heat source. To check the calculated rate of heat transfer from the inner slug to the outer slug, unirradiated Mark 31A inner slugs will be placed in a housing to simulate the outer slug column and will be heated internally. The housing temperature will be maintained at about 100°C and the slug temperature will be measured as a function of heating rate. Use of actual inner slugs is necessary to achieve emissivity and rib contact that approach the actual case. The heated section will be long enough to avoid erroneously low temperatures due to end effects. One or more ribs will be insulated in some of the tests to determine the effect of reduced rib contact. Test results will be available by mid-summer.

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1. J. M. Boswell to K. W. French, "Charge-Discharge Emergency Cooling Needs", to be issued.

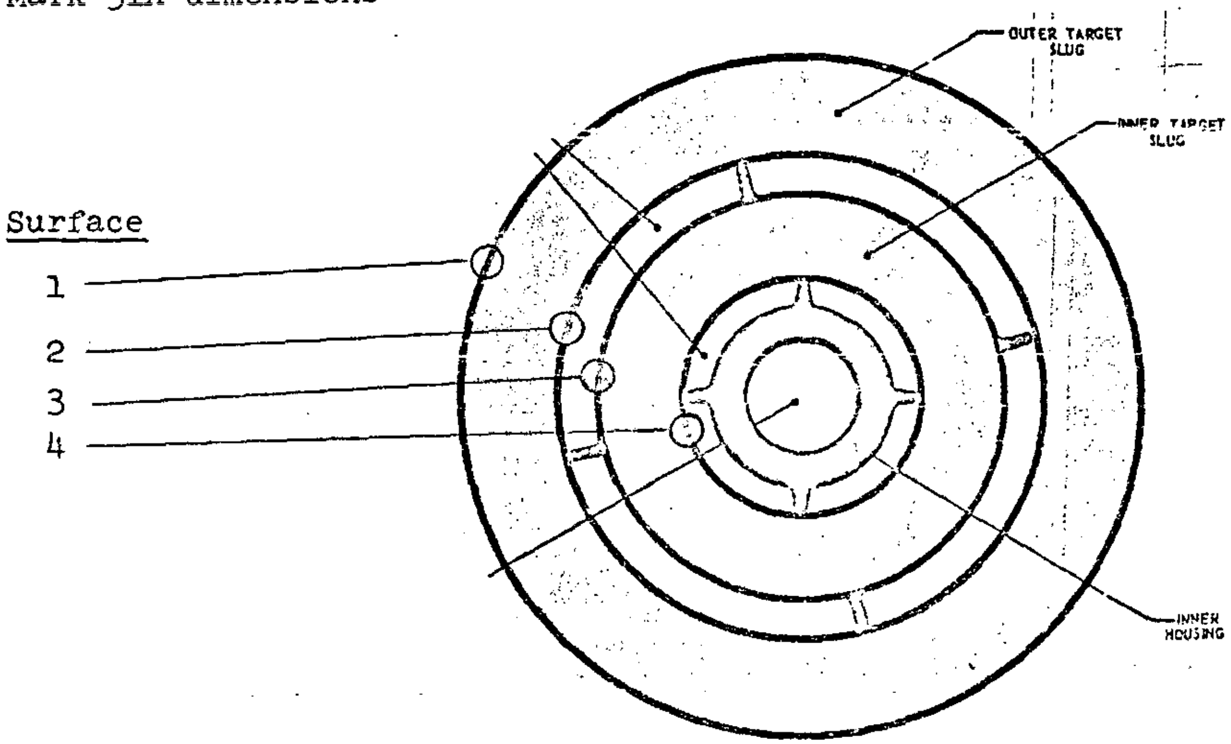
2. P. L. Gray, "Spray Cooling for Dropped Fuel Elements", DPSP-61-2383 (RTM 2323), August 23, 1962 (Secret).

3. W. H. Gleaves, "Cooling of Dropped Mark V-B Assembly", DPST-61-383, July 20, 1961 (Secret).

APPENDIX A

HEAT REMOVAL FROM MARK 31A WITH EXTERNAL SPRAY

1. Mark 31A dimensions



Surface	Diameter, inches Clad	Unclad
1	3.700	3.640
2	2.590	2.650
3	2.200	2.160
4	1.250	1.310

Slug length (inner and outer)

Clad 8.720 inches

Unclad 8.320 inches

Slug Weight, Outer 28.4 lbs.

Inner 13.5 lbs.

Inner Slug Ribs:

Rib Circle OD 1.256 inches

Rib Height 0.170 inches

Rib Thickness 0.062 inches

2. Nomenclature

q = heat flow or heat generation, pcu/hr

q_v = volumetric heat generation, pcu/hr ft^3

t = temperature, ^oC

T = temperature, ^oK

d = diameter, ft

L = length, ft

r = radius, ft

A = surface area, ft^2

h = heat transfer coefficient, pcu/hr $ft^{2\,o}C$

k = thermal conductivity, pcu/hr ft^oC

W = water flow, lb/hr

S = water spray density, lb/hr ft^2

c = heat capacity, pcu/lb^oC

Subscripts

o = outer slug

i = inner slug

t = total, inner + outer

1, 2, 3, 4 = surface identification

w = water

u = uranium

Al = aluminum

a = air

3. Decay Heat

a) Assembly Power = 29 kw (This is the most restrictive limit on power at discharge based on adequate heat removal from an assembly horizontal in the discharge basin, from DPSTM-31H, reference 17).

b) Power ratio, inner slugs/outer slugs = $^{29}/_{71}$ (from DPSTM-31H)

c) Axial power profile, $^{max}/_{avg}$ = 1.3

d) Max outer slug power, q_o = 2807 pcu/hr

e) Max inner slug power q_i = 1157 pcu/hr q_t = 3964 pcu/hr

4. Outer Slug Temperature

a) Heat flux on outer surface = $\frac{q_t}{A_1}$ = 5600 pcu/hr-ft^2

(all heat from inner and outer slugs passes through outer surfaces)

b) Heat transfer coefficient with water spray on outer surface, h_1:

- From reference 15, Dupont standard DG55C, Fig 4, for water flowing by gravity over horizontal tubes, h is a function of $\frac{W}{2L\ell}$.
- For spraying water, assume $W = SL\ell$

  ($L\ell$ = projected area of slug)
- For average rate of existing sprays, 0.6 gpm/ft^2

$$S = 300 \text{ lb/hr ft}^2\text{, and } W = 67 \text{ lb/hr}$$

$$\frac{W}{2L\ell} = \frac{SL\ell}{2L\ell} = \frac{S}{2} = 150 \text{ lb/hr ft}^2$$

and h_1 = 340 pcu/hr ft^2 °C

c) Outer slug surface temperature, t_1:

$$t_1 = \text{avg } t_w + \frac{q_t}{A_1 \, h_1}$$

$$\text{avg } t_w \cong 20^\circ C + \frac{\Delta t_w}{2}$$

assuming spray water at 20°C

$$\Delta tw = \frac{q_t}{W} = \frac{3964 \text{ pcu/hr}}{(67 \text{ lb/hr})(1 \text{ pcu/lb}^\circ C)}$$

$$\Delta t_w = 59^\circ C$$

$$\text{avg } t_w = 20 + \frac{59}{2} = 50^\circ C$$

$$t_1 = 50 + \frac{3964 \text{ pcu/hr}}{(0.703 \text{ ft}^2)(340 \text{ pcu/hr ft}^{2\,\circ}C)}$$

$$t_1 = 50 + 16.6^\circ C = 67^\circ C$$

d) Outer slug inner surface temperature, t_2:

$$t_2 = t_1 + \underbrace{\frac{q_i \ln(r_1/r_2)}{2\pi L k_u}}_{\substack{\Delta t \text{ from } q_i \text{ transferred} \\ \text{across outer slug}}} + \underbrace{\frac{q_o\left[r_1^2 - r_2^2 - 2r_2^2 \ln(r_1/r_2)\right]}{4\pi(r_1^2 - r_2^2)\, L\, k_u}}_{\substack{\Delta t \text{ from } q_o \text{ generated} \\ \text{within outer slug}}}$$

$$t_2 = 67^\circ C + 4.8^\circ C + 5.2^\circ C$$

$$t_2 = 77^\circ C$$

(In above calculation, the aluminum cladding was ignored because temperature rise across the aluminum is negligible; only unclad dimensions were used.)

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4. Inner slug temperatures

a) Heat transferred from inner to outer slug by conduction through air, $(q_i)_{air}$:

$$(q_i)_{air} = \frac{2\pi L k_a \,(t_3 - t_2)}{\ln\left[\frac{r_2}{r_3}\right]} = 0.68\,(t_3 - t_2)$$

$(k_a = 0.025$ pcu/hr ft°C$)$

b) Heat transferred from inner to outer slug by conduction through ribs $(q_i)_{ribs}$:

- o $(q_i)_{ribs}$ is controlled by the number of ribs in contact and the contact coefficient h_c.
- o From reference 6, h_c is about 450 to 550 pcu/hr ft^2°C for rough aluminum surfaces, contact pressure in the range of 12-25 psi (corresponding to the weight of an inner slug supported by 1 or 2 ribs), and temperature under 100°C. For a contact pressure of only 1 psi, h_c is still about 300 pcu/hr ft^2°C. For smooth surfaces h_c is about 2000 pcu/hr ft^2°C.
- o For this calculation a contact coefficient of 300 pcu/hr ft^2°C was chosen to allow for uncertainties such as aluminum oxide buildup. (The thermal conductance of 0.001 inch of aluminum oxide, however, is about 9600 pcu/hr ft^2°C, so a considerable buildup would be required for substantial reduction of h_c).
- o $(q_i)_{ribs} = n\, h_c\, A\, (t_3 - t_2)$

  where: N = number of ribs in contact

  A = rib contact area, ft^2

$$(q_i)_{ribs} = 1.13\, n\, (t_3 - t_2)$$

c) Heat transferred from inner to outer slug by radiation

From reference 6, DuPont standard DG70C

$$(q_i)_{radiation} = h_r A\, (t_3 - t_2)$$

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where: $h_r = F_a F_\epsilon \left[\dfrac{\left(\frac{T_3}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4}{t_3 - t_2} \right]$

or, in more familiar form,

$$(q_i)_{radiation} = b\ A\ F_a F_\epsilon\ (T_3^4 - T_2^4)\ .$$

where: b = Stephan-Boltzman constant, 1×10^{-8} pcu/hr ft^2($^\circ$K)^4

F_a = angle factor = 1 for completely enclosed body

F_ϵ = emissivity factor = $\dfrac{1}{\dfrac{1}{\varepsilon_3} + \dfrac{1}{\varepsilon_2} - 1}$

ε = emissivity

T = temperature, $^\circ$K

A = area, ft^2 (of hot surface)

From DG86C, Table 2 (ref.15), for dull aluminum

ε_3 at ~ 500°C, = 0.3 to 0.5

ε_2 at < 100°C = 0.2 to 0.3

Assume $\varepsilon_3 = 0.3$ and $\varepsilon_2 = 0.2$

Then $F_\varepsilon = 0.136$

and $(q_i)_{radiation} = 5.7 \times 10^{-10}\ (T_3^4 - T_2^4)$

d) By assuming the inner slug surface temperature t_3, and solving

$(q_i)_{air} = 0.68\ (t_3 - t_2)$

$(q_i)_{ribs} = 1.13\ n\ (t_3 - t_2)$

$(q_i)_{radiation} = 5.7 \times 10^{-10}\ (T_3^4 - T_2^4)$

we arrive at the following :

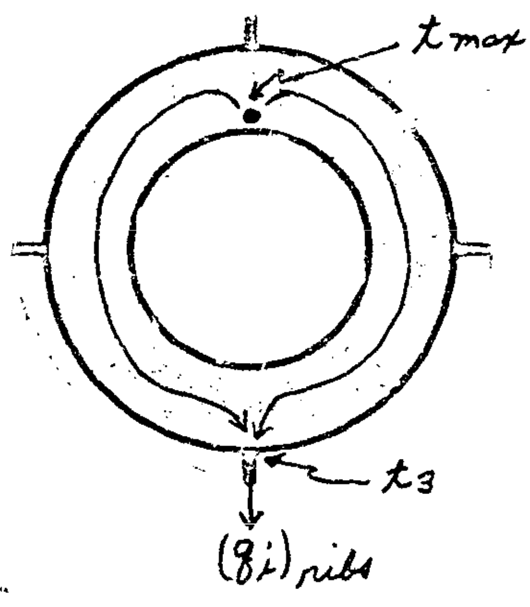
t_3 °C	$(q_i)_{air}$, pcu/hr	$(q_i)_{ribs}$, pcu/hr 1 rib*	2 ribs*	$(q_i)_{radiation}$, pcu/hr	$(q_i)_{total}$ pcu/hr No ribs*	1 rib*	2 rib
400	219	365	730	101	320	685	1050
500	289	478	956	185	474	952	1430
600	356	591	1182	307	663	1254	1845
700	424	704	1407	494	918	1622	2326
800	492	817	1634	726	1218	2035	2852
900	560	930	1860	1038	1598	2528	3458

* Number of ribs in contact with outer slug

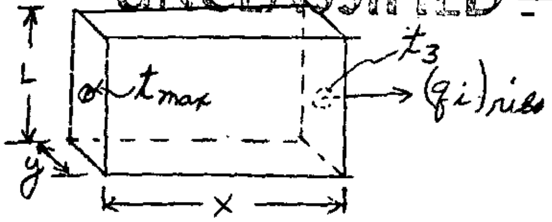
$(q_i)_{total}$ available = 1157 pcu/hr, so:

Number of ribs in contact	t_3 °C	$(q_i)_{air}$, pcu/hr	$(q_i)_{ribs}$, pcu/hr	$(q_i)_{radiation}$ pcu/hr
2	430	240	798	119
1	575	339	563	255
0	780	478	-	679

e) Temperature gradient within inner slug with rib contact :



Assume that the portion of the total heat $(q_i)_{total}$ that is transferred across the ribs, $(q_i)_{ribs}$, travels circumferentially around the slug following the model below.



$$y = \frac{d_3 - d_4}{2} = \text{slug thickness}$$

L = slug length

x = a portion of the slug circumerence at the average diameter

$$t_{max} - t_3 = \frac{q_v (x)^2}{2 k_u}$$

where q_v = volumetric heat generation

$$q_v = \frac{(q_i)_{ribs}}{\frac{\pi}{4} (d_3^2 - d_4^2) L}$$

(clad dimensions are used because the aluminum cladding will conduct a considerable amount of heat).

For 1 ribs in contact;

$$x = \left[\frac{180^\circ}{360^\circ}\right] (\pi) \left[\frac{d_3 + d_4}{2}\right] = 0.23 \text{ ft}$$

$(q_i)_{ribs}$ = 563 pcu/hr

and $t_{max} - t_3 = 54^\circ C$

$t_{max} = t_3 + 54^\circ C = 575 + 54 = 629^\circ C$

For 2 ribs in contact:

$$x = \left[\frac{112.5^\circ}{360^\circ}\right] (\pi) \left[\frac{d_3 + d_4}{2}\right] = 0.14 \text{ ft}$$

qi = 798 pcu/hr

$t_{max} - t_3 = 30^\circ C$

$t_{max} = t_3 + 30^\circ C = 430^\circ + 30^\circ = 460^\circ C$

f) Temperature gradient within inner slug with no rib contact.

$$t_4 - t_3 = \frac{q_v \left[r_3^2 - r_4^2 - 2r_4^2 \ln \frac{r_3}{r_4} \right]}{4\, k_u}$$

$$t_4 - t_3 = \frac{q_i \left(r_3^2 - r_4^2 - 2r_4^2 \ln \frac{r_3}{r_4} \right)}{4\, k_u \pi L \left(r_3^2 - r_4^2 \right)}$$

$$t_4 - t_3 = 2.6^\circ C$$

This temperature difference is negligible compared to the uncertainties in the other portions of the calculations (eg, heat transfer across rib contact) and can be ignored.

APPENDIX B

DIFFUSION OF FISSION PRODUCTS FROM HOT IRRADIATED URANIUM

Diffusion of fission product gases from uranium would be very slow according to data in the literature (references 8,9,16); at temperatures under 900°C less than 1% of the Xenon and Krypton would escape in 100 days. Release of iodine would be less than that of Xenon and Krypton (reference 8). Release fraction of Xenon and Krypton vs time and temperature is shown in Figure 1, and details of the diffusion calculations follow.

1. From reference 16, pg 555 and reference 9, pg 13, for diffusion of Xe and Kr from uranium,

$$f = \frac{S}{V}\sqrt{\frac{Dt}{\pi}}$$

where: f = fraction of gas diffusing in time t to

S = exposed surface area, cm^2

V = volume of uranium, cm^3

t = time, sec

D = diffusion coefficient, cm^2/sec

2. From reference 16, diffusion coefficients for Xe and Kr are approximately;

Temperature, °C	D, cm^2/sec
650	2×10^{-15}
770	7×10^{-14}
900	2×10^{-13}

The curve in Figure 1 was calculated using the diffusion equation and these coefficients.

The following data were extracted from reference 9. These data represent a number of tests by different people.

Reference Page	Temperature, °C	Time	% of Fission Products Released	
			Rare Gases	Iodine
11	600	30 hours	0.14	0.001
"	1000	" "	1.25	0.5
11	600	33 hours	0.04	0.007
12	1000	66 hours	2.12	0.98
18	980	5 days	Nil	-
"	1000	21.6 days	"	-
"	1025	29.2 days	3.7	-
"	1050	15 days	39	-
"	1075	9.25 days	64	-

From the data above, and from the diffusion data in reference 16, it is evident that fission product release by diffusion is very low at temperatures under 1000°C.

FIGURE 1

DIFFUSION OF XENON AND KRYPTON FROM HOT URANIUM